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On Noise and Interference Modeling for Over-the-air Testing of MIMO Terminals

Wei Fan, Pekka Kyosti, Yilin Ji and Gert F. Pedersen

***Abstract*—As the fifth generation (5G) ecosystem matures, the time for large-scale 5G radio commercialization is now. Over-the-air (OTA) radiated testing is seen to replace currently dominantly adopted cable conducted testing for upcoming radio systems due to integrated antenna designs. To properly evaluate performance of radio systems in fading channel conditions, it is typically needed to model the realistic signal, interference and noise conditions in the testing environment. However, interference and noise modeling is largely overlooked in the literature in OTA testing, since the discussion is typically focused on the signal alone. In this paper, interference and noise modeling in three OTA setups, including the multi-probe anechoic chamber (MPAC), radiated two stage (RTS) and reverberation chamber (RC) is discussed and summarized.**

***Index Terms*—Over-the-air Testing, noise modeling, MIMO performance, radio channel models**

I. Introduction

Over-the-air (OTA) testing of multi-antenna systems has been actively discussed in the past ten years [1], [2]. In OTA testing, the device under test (DUT) is connected to the test instrument via radio waves, i.e. over-the-air. The DUT is typically placed in a controllable and shielded laboratory environment. Radiated over-the-air (OTA) testing is seen as inevitable for future 5G radios due to their highly compact and integrated designs [3]–[5]. Antennas in future radio systems will be integrated directly into radio frequency (RF) transceiver circuits, leaving no space for RF connectors. As a result, it will become impractical to use traditional cable conducted setups for wireless system performance testing, which brings the need for OTA radiated testing. OTA testing plan for 2×2 downlink multiple-input multiple-output (MIMO) and transmit diversity has been standardized, where the multi-probe anechoic chamber (MPAC) method and the radiated two stage (RTS) methods have been selected, due to their capability to reproduce spatial channel models for MIMO performance testing [1], [2], [6], [7]. Standardization work on OTA testing for 5G terminals is currently under discussion in CTIA and 3GPP.

Noise and interference modeling is an integral part of MIMO terminal testing, since the signal, interference and noise components play equal roles in determining MIMO system performance metrics. A test system that fails to properly model noise and interference cannot be expected to accurately predict MIMO performance. Interference modeling will be even more important in future radios, due to congestion of radios in the spectrum and tendency to reduce cellular network cell size. However, the focus of most works reported in the literature on OTA testing has been on modeling the signal components only, while noise and interference modeling is largely overlooked.

Noise is unwanted random signal that is always present in the receiver (Rx), in addition to the received desired signals and interference. Therefore, noise is typically internally generated at the Rx. Interference, on the other hand, is generated from external source. It can be caused by other modulated signal (e.g. LTE or 5G new radio (NR) signals), or simply noise type of signals (e.g. white Gaussian noise). For example, microwave oven signals at 2.45 GHz, is more noise-like signal, which can impact radio communication around that frequency. It is seen as interference signal since it is received from external source. In the testing industry, noise is typically modelled as AWGN signals at the Rx, while interference signal can be generated as modulated signal, with or without fading, or simply as noise type of signals. The interference can be emulated with different levels of realism to save testing cost. As explained, the main difference between noise and interference is the source. As interference is external to the receiver, it is observed as correlated in the Rx antenna. Therefore, it is possible to remove interference by receiver signal processing techniques (e.g. interference cancellation technique) to improve radio communication performance. However, noise, which is internal to the receiver, is not possible to remove since it is uncorrelated in any dimension (i.e. space, frequency, time). In real world situation, the noise is mostly generated from the RF chain of the Rx. However, it is still essential in the hardware emulation. This is partly motivated by the need to evaluate radio performance with specific signal-noise-ratio (SNR). In the hardware emulation, although the noise is internally generated in the Rx in any cases, its exact level, however, is typically not known. Therefore, we need to emulate the noise, which dominates over the internal "self noise", to achieve the intended SNR in the Rx.

In OTA setups, the ways of modeling noise and interference are largely overlooked, though some discussions exist in standardization meetings. Previous studies of OTA testing have carefully modeled the radio channels for the signal component. However, little attention has been paid on modelling characteristics of noises and interference at the DUT receivers in various OTA setups. The focus of the paper is to summarize how interference and noise are modelled in three OTA setups, namely, the MPAC, RTS and reverberation chamber and their capability to reflect the wanted interference and noise characteristics.

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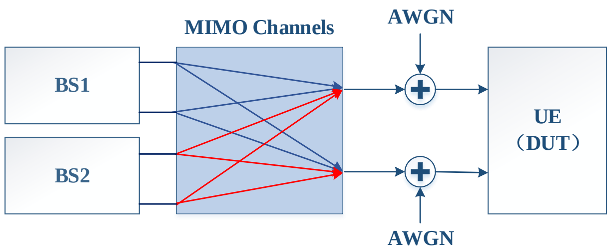

Figure 1. Illustration of the cable conducted setup for 2×2 MIMO receive test. BS1 is the serving cell and BS2 is the interfering cell.

II. Noise and Interference Modeling in Cable Conducted Setup

An illustration of the conventional cable conducted setup is depicted in Fig. 1, where a simple 2×2 MIMO is selected as an example [8]. The signal model for the conducted setup can be written as

$$\boldsymbol{y}(f,t) = \boldsymbol{H_T}(f,t)\boldsymbol{x_1}(f,t)+\boldsymbol{H_I}(f,t)\boldsymbol{x_2}(f,t)+\boldsymbol{n}(f,t), \quad (1)$$

where $\boldsymbol{H_I}(f,t) \in \mathbb{C}^{N\times M}$ and $\boldsymbol{H_T}(f,t) \in \mathbb{C}^{N\times M}$ is the time-variant wideband MIMO channel frequency response between the M Tx antenna ports to the N Rx antenna ports for the interfering signal and desired signal, respectively, $\boldsymbol{x_1}(f,t) \in \mathbb{C}^{M\times 1}$ and $\boldsymbol{x_2}(f,t) \in \mathbb{C}^{M\times 1}$ are the transmit signal vector at the BS1 antenna ports and BS2 antenna ports, respectively, $\boldsymbol{y}(f,t) \in \mathbb{C}^{N\times 1}$ and $\boldsymbol{n}(f,t) \in \mathbb{C}^{N\times 1}$ are the receive signal vector and noise vector at the DUT antenna ports, respectively. The MIMO channel response can be typically generated following either the geometry-based stochastic channel model (GBSC) principle [9], [10] or the correlation based channel model principle [11], [12].

1) Signal: The base station (BS) emulator generates test signals, which are fed to a fading channel emulator (CE). MIMO fading channels are generated in the CE. The Tx signals are then convolved with the MIMO channels in the CE, and the output signals are transmitted to the DUT antennas via radio frequency (RF) cables.

2) Interference: As explained, The interference can be emulated with different levels of realism in testing. For a simple case, interference can be modelled as simple noise-like signal. This can be easily generated in the channel emulator. For a more complicated case, we can generate interference as external modulated signal with or without fading channel models. An illustration of interference modelled as modulated signals with fading channel model are shown in Fig. 1.

3) Noise: Additive white Gaussian noise (AWGN) can be generated in a noise generator and added to the signals directly, as illustrated in Fig. 1. For MIMO terminal receiver testing in the conventional conducted setup, noise is typically generated to be statistically independent and uncorrelated at the DUT receiver. The SNR can be controlled in the hardware emulation such that the signal level is rather high and the noise power is adjusted accordingly. It is done this way to prevent the domination of the true internal Rx noise. The AWGN noise can be generated in the CE as well to save noise generator resource.

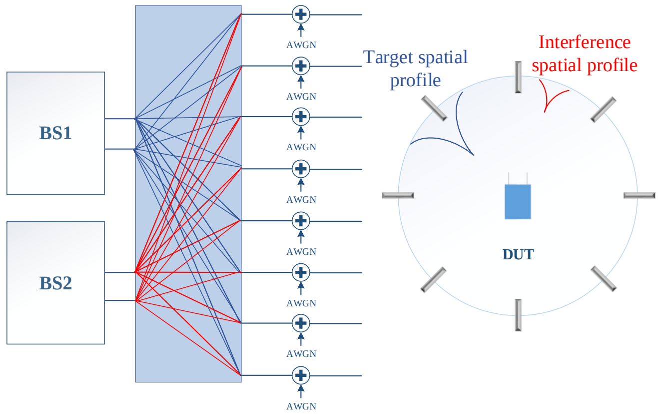

Figure 2. Illustration of the MPAC setup with spatially uniform noise and spatial fading interference for 2×2 MIMO receive test.

III. Noise and Interference Modeling in OTA Setup

A. Multi-probe anechoic chamber (MPAC) OTA setup

A simplified MPAC setup is shown in Fig. 2, which typically consists of BS emulator (a serving BS and an interfering BS), a fading CE, an anechoic chamber and a number of probe antennas uniformly placed around the DUT. The basic idea of the setup is that realistic propagation channels can be physically reproduced inside a test area where the DUT is located, via controlling the signal radiated from the probe antennas. Therefore, the DUT can be tested as it would be used in reality.

The signal model can be expressed as:

$$\begin{aligned}\boldsymbol{y}(f,t) &= [\hat{\boldsymbol{H}}_{\boldsymbol{T}}(f,t)\boldsymbol{x_1}(f,t) + \hat{\boldsymbol{H}}_{\boldsymbol{I}}(f,t)\boldsymbol{x_2}(f,t)] + \hat{\boldsymbol{n}}(f,t)\\ &= \boldsymbol{F}[\boldsymbol{H_T}^{ota}(f,t)\boldsymbol{x_1}(f,t) + \boldsymbol{H_I}^{ota}(f,t)\boldsymbol{x_2}(f,t)]\\ &\quad + \boldsymbol{F}\boldsymbol{n}^{ota}(f,t), \qquad (2)\end{aligned}$$

where $\boldsymbol{H_I}^{ota}(f,t) \in \mathbb{C}^{K\times M}$ and $\boldsymbol{H_T}^{ota}(f,t) \in \mathbb{C}^{K\times M}$ denote the channel frequency response between the M Tx antenna ports to the K OTA probes, i.e. channel profiles implemented in the fading channel emulator to emulate the interference and target channel profile. $\boldsymbol{F} \in \mathbb{C}^{N\times K}$ is the transfer coefficient matrix between the N DUT antenna ports and K probe antennas, which can be determined by the probe antenna pattern, the line-of-sight (LoS) free space propagation, and the DUT antenna pattern. $\boldsymbol{n}^{ota}(f,t) \in \mathbb{C}^{1\times K}$ is the independent and identically (i.i.d) distributed noise terms added to the K probe antennas.

1) Signal component: According to [1], [2], target channel models, e.g. SCME Urban macro (UMa) and urban micro (UMi) spatial channel models [9], [10], are emulated in the test area. Extensive studies on channel emulation techniques exist in the literature on how to generate $\boldsymbol{H_T}^{ota}(f,t)$ in the MPAC setup, see detailed discussion in [4], [7]. How well $\hat{\boldsymbol{H}}_{\boldsymbol{T}}(f,t)$ statistically mimics the target $\boldsymbol{H_T}(f,t)$ is mainly determined by the system resource (i.e. number and location of the probe antennas and fading emulator resource).

2) Interference component: An example to model interference as modulated signal with fading channel model is illustrated in Fig. 2. The fading channel model for interference signal can be treated the same way as for the signal component,

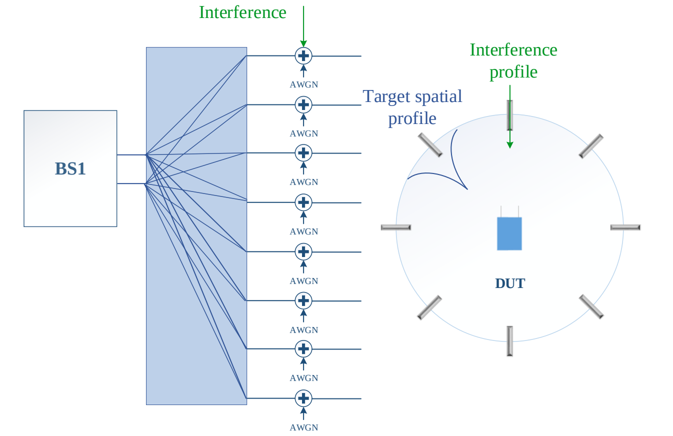

Figure 3. Illustration of the MPAC setup with spatially uniform noise and simple non-fading interference for 2×2 MIMO receive test.

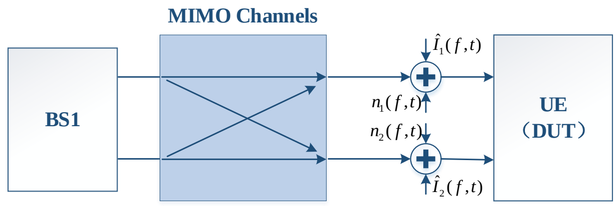

Figure 4. Illustration of the conducted two stage setup with correlated noise for 2×2 MIMO receive test.

although a different spatial channel profile can be utilized. Again, the interference modelling can be simplified to save cost. For example, a directionally non-dispersed non-fading interference is illustrated in Fig. 3. The added interference could be either noise or some modulated (but still non-fading) sequence.

3) Noise component: As for the noise profile, uniform spatial profile is typically adopted in OTA testing in the MPAC setup. Therefore equal power is allocated to the independent AWGN generators, as shown in Fig. 2. Note that noise can be generated internally in the channel emulator as well to save the external noise generators. For MIMO OTA downlink testing, the DUT should be exposed to the desired testing signal and noise conditions to mimic realistic scenarios. Note that the noise power is typically varied to mimic different SNR conditions in the throughput performance testing.

Note that the noise power is constant during DUT antenna rotation due to uniform noise spatial profile, while the signal power varies during DUT rotation due to directive spatial channel profile for the signal component. As a result, the SNR would vary when the DUT rotates, which agrees with what we would expect in practice. Note that in the MPAC setups, both non-uniform and uniform noise power angular distributions can be generated. Besides the uniform spectra we discussed, we can also transmit noise with same power angular spectra as the signal. The non-uniform noise power spectra is desired in cases, e.g. when we would need same SNR regardless of the DUT orientation or beamforming gain.

Assume we have two Rx antennas on the DUT, the received noises at the two antennas can be expressed as, respectively:

$$\hat{n}_1(t) = \sum_{k=1}^{K} G_1(\phi_k) n_k^{ota}(t) L_{k,1} \exp(j2\pi d_{k,1}/\lambda) \tag{3}$$

$$\hat{n}_2(t) = \sum_{k=1}^{K} G_2(\phi_k) n_k^{ota}(t) L_{k,2} \exp(j2\pi d_{k,2}/\lambda), \tag{4}$$

where $d_{k,1}$ and $d_{k,2}$ are the propagation distance between the k-th probe and receive antenna 1, and receive antenna 2, respectively. L presents the path loss term, which can be assumed the same for compact DUTs and large anechoic chamber. G_1 and G_2 denote the complex antenna pattern of antenna 1 and 2, respectively. ϕ_k denotes the probe angle for $k \in [1, K]$, and λ is the wavelength.

The correlation coefficient between received noises at the DUT antenna ports can be expressed as, according to the correlation definition:

$$\begin{aligned}\mathrm{corr}(\hat{n}_1(t), \hat{n}_2(t)) &= \frac{\mathrm{cov}(\hat{n}_1(t), \hat{n}_2(t))}{\sqrt{\mathrm{cov}(\hat{n}_1(t), \hat{n}_2(t))\mathrm{cov}(\hat{n}_1(t), \hat{n}_2(t))}} \\ &= \frac{\sum_{k=1}^{K} G_1(\phi_k) \cdot G_2^*(\phi_k) \exp(j2\pi(d_{k,1} - d_{k,2})/\lambda)}{\sqrt{\sum_{k=1}^{K} |G_1(\phi_k)|^2 \sum_{k=1}^{K} |G_2(\phi_k)|^2}}\end{aligned} \tag{5}$$

where $\mathrm{corr}()$ and $\mathrm{cov}()$ are the correlation and covariance operator, respectively.

As can be seen, the noise received at the DUT antenna ports in the MPAC setup will be spatially correlated. Further, its correlation coefficient is determined by the DUT antenna element pattern and spacing, which are typically unknown in the OTA testing. As a result, the noise correlation, which will exist in the MPAC setups, is typically unknown and uncontrollable. In any case, the noise correlation is typically low, when we have uniform PAS for the noise and DUT antenna spacing larger than 0.4 λ. The only case where the noise correlation can be high is when DUT antennas are highly directive and point to the same direction. However, this may only happen with frequency region (FR)2 beamforming DUT in rare conditions.

B. Two-stage Method

1) Conducted Two stage setup: The principle of conducted two-stage method is originally described in [13]. With the conducted two stage method, antenna patterns of the DUT elements are measured in an anechoic chamber in the first stage in a non-intrusive manner. The measured antenna patterns are embedded with the target channel models in the fading CE, and then the output signal of the fading CE is guided directly to the DUT via RF cables, same as used in the traditional conducted testing. The interference component can be modeled as modulated signal with fading channel, as the signal component, as demonstrated in (1) and (2). It can also be modeled as noise like signal, as described in (6) below. The signal model of the setup can be expressed as

$$\boldsymbol{y}(f,t) = \boldsymbol{H}(f,t)\boldsymbol{x}(f,t) + \hat{\boldsymbol{I}}(f,t) + \boldsymbol{n}(f,t). \tag{6}$$

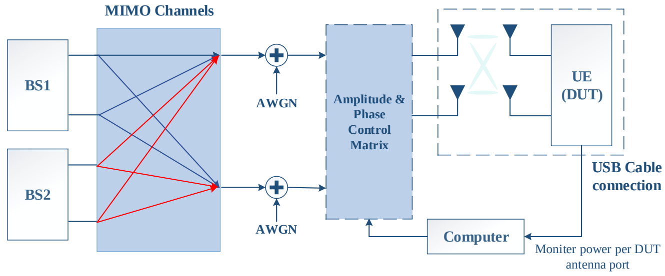

Figure 5. Illustration of the proposed setup for 2×2 MIMO receive test with arbitrary noise correlation.

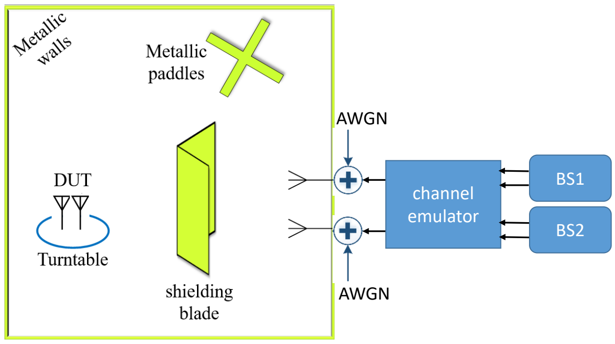

Figure 6. Illustration of the RS setup for 2×2 MIMO receive test.

The target channels selected for the signal component are spatial channels, e.g. SCME UMi or SCME UMa as for MIMO terminal performance testing [6], [13].

The interference term $\hat{\boldsymbol{I}}(f,t)$ received at the DUT ports can be written as

$$\hat{\boldsymbol{I}}(f,t) = \boldsymbol{B} \cdot \boldsymbol{n}(f,t), \tag{7}$$

where $\boldsymbol{B}$ is a matrix to generate the desired interference correlation according to the spatial channel profile and DUT antenna patterns. Correlated interference modeling in the conducted two-stage setup is discussed in [2], [14]. The correlated interference term is generated via applying omni-directional channel and DUT antenna patterns. The entries in $\boldsymbol{B}$ are tuned so that the correlation between the two noise terms $\hat{i}_1(f,t)$ and $\hat{i}_2(f,t)$

$$\rho_{\hat{i}_1,\hat{i}_2} = \frac{\int G_1(\phi)G_2(\phi)^* \,\mathrm{d}\phi}{\sqrt{\int |G_1(\phi)|^2 \,\mathrm{d}\phi \cdot \int |G_2(\phi)|^2 \,\mathrm{d}\phi}}, \tag{8}$$

is achieved.

The uncorrelated noise term is added at the output port of the channel emulator. Similar to the MPAC setup, the SNR would vary when the DUT rotates during testing (which is virtually realized via mathematically rotating the antenna pattern in the fading emulator).

The conducted two-stage method can offer desired signal, interference and noise testing conditions with reduced requirement for CE and noise generators. However, the conducted two-stage method has been challenged for its lack of support for OTA radiated setup [3], [6].

2) Radiated two stage method: A radiated two stage (RTS) test method is presented in [6], where the problem of connecting an RF cable to the DUT receiver is eliminated via calibrating out the transfer matrix between the probe antennas and DUT antennas in the fading emulator.

The second step of the RTS method, which aims to replace cable conducted setup with the wireless cable, is described in the literature [9]. The wireless cable method, which avoids the RF cables and achieve cable connection functionality, has drawn great attention from industry and academia in recent years as an alternative to replace conventional cable conducted setups. With the interference modelled the same way as the signal component, the signal model of the proposed setup can be expressed as:

$$\begin{aligned}\boldsymbol{y}(f,t) =& \boldsymbol{A}\boldsymbol{G}\big[[\boldsymbol{H_T}(f,t)\boldsymbol{x_1}(f,t) + \boldsymbol{H_I}(f,t)\boldsymbol{x_2}(f,t)] \\ &+ \hat{\boldsymbol{n}}(f,t)\big],\end{aligned} \tag{9}$$

where $\boldsymbol{A} \in \mathbb{C}^{N\times K}$ denotes the transfer matrix between the K probe antenna ports and N DUT antenna ports, and $\boldsymbol{G} \in \mathbb{C}^{K\times N}$ denotes the compensation matrix, which is implemented by the amplitude and phase control matrix. In the wireless cable setup, the desired signal, interference and noise terms can be guided to the respective DUT antenna ports over-the-air, without cross-talks to other antenna ports, as shown in Fig. 5. To achieve this purpose, we need to design the compensation matrix $\boldsymbol{G}$ such that $|\boldsymbol{A}\boldsymbol{G}| \approx \boldsymbol{I}_{N\times N}$ can be achieved, with $\boldsymbol{I}_{N\times N} \in \mathbb{R}^{N\times N}$ an identity matrix. Different methods to achieve wireless cable connection have been discussed in the literature [3], [6], [15]. In [15], a calibration method is proposed to eliminate the RF connection. The basic idea is that we can determine the transfer matrix $\boldsymbol{A}$ via setting the amplitude and phase control matrix and monitoring the respective recorded power per DUT antenna ports. The optimal amplitude and phase weight is found when the isolation between wanted signal transmission and unwanted cross-talks are maximized. The method works for arbitrary wireless devices supporting MIMO standards in a compact anechoic box.

C. RC OTA setup

The reverberation-chamber (RC) testing is carried out in an enclosed metallic cavity, where the statistically isotropic multipath environments are emulated by moving metallic paddles and rotating turntables as illustrated in Fig. 6. Note that the channel emulator might not needed/available in some RC setups.

The way of applying noise in the RC setup is briefly explained in [2]. Basically, the noise is added to the test signal directly before it is radiated through the test antenna. As thoroughly investigated in the literature, the RC emulates rich multipath environments with statistically isotropic angular distribution and Rayleigh fading channels [16], [17]. Therefore, similar to the test signal, the noise will experience Rayleigh fading channels with statistically isotropic angular distribution before reaching the DUT antenna ports. Note that this differs from the aforementioned test setups where injected noise term is not faded (i.e. no fading channels applied to the noise term). The noise correlation seen at the DUT ports will be the same as the signal correlation in the RC setups. Further, the SNR would not vary when the DUT rotates during testing. There are several undesirable effects for noise modeling in the RC setup for OTA testing. The noise will be spatially correlated, due to the isotropic impinging power spectrum, as explained. Further, the noise might be temporally correlated as well (which is caused by Doppler spectra profile in RC), as the stirrers are moving continuously. In a large RC setup with non-negligible delay spread, the noise will be correlated in the frequency domain as well.

IV. Conclusion

In this paper, we summarized how noise and interference components are modeled in the OTA setup. The interference component, depending on the level of realism, can be typically modeled as simple noise-like signal, or modulated signals with fading channel models as the target signal. As for the noise term, uncorrelated noise term can be generated in the conducted setup and also the radiated two-stage setup in principle. As for the MPAC setup, the noise term at the Rx will be spatially correlated. For the RC setup, the noise term will be unavoidably correlated in spatial, temporal and also frequency domains, which are undesirable effects in testing.

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